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MECHANICAL PROPERTY CHARACTERIZATION

OF

A588 STEEL PLATES AND WELDMENTS

Data Survey

by

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ABSTRACT

ASTM A588 steels are widely used in the constructional industry for buildings and bridges and have been adopted by many pressure vessel manufacturers for supports and other related applications. This survey summarizes for the most part unpublished data on the strength, toughness, and weldability of A588 Grade A and Grade B steel as influenced by heat treatment and processing. Although the material easily meets specified levels of strength, its toughness can vary extensively depending on the level specified, the processing prior to delivery and subsequent fabrication operations. Notch toughness, through-thickness properties, and fatigue crack growth characteristics can be strongly influenced by special processing available from steel suppliers. An important finding is that toughness requirements must be specified if improvement over ordinary carbon-manganese structural steels is desired. Although the hardenability of A588 steels is somewhat higher than lower alloy carbon-manganese steels, it can be readily welded using well established preheat and consumable specifications. The heat affected zone in A588 steels provides acceptable strength and toughness over a wide range of welding heat input both as-welded and after post weld heat treatment.

INTRODUCTION

This paper is a response on the part of the Pressure Vessel Research Committee to a request by pressure vessel manufacturers and users for information about the mechanical properties, especially toughness, that can be expected of steels in the ASTM A588 specification.[1] It was recognized that although this steel is not used in pressure vessels themselves, it was and is widely employed for pressure vessel supports and other types of construction related to the pressure vessel industry. In this context the steel is used because it has a somewhat higher yield strength than the ordinary carbon-manganese steels, such as A36, and because there is a general belief that improved toughness can be obtained from this grade. Some of the material purchased has had toughness specifications applied to it and the experience of fabricators has been that the material can meet these specifications. In many instances the requirements have been moderate, 15 ft-lbs at 40°F, (20 J at 5°C) and the material can be purchased to this specification. Other fabricators have purchased A588 steels without such a specification under the assumption that good toughness will naturally be characteristic of this product. In most instances, however, it is the higher strength level obtainable that has made its selection attractive.

The A588 steels were developed for a wide range of structural applications of which pressure vessel supports are only a very small fraction. A much larger portion of this material goes into buildings and bridges, and at the present time, it commands almost half of the steel bridge construction market. In some of these applications it is used in the unpainted condition to take advantage of its weathering characteristics. In spite of its wide use in such applications for over 30 years, its adoption by the pressure vessel industry was slow. There were and still are questions relating to its general suitability in the pressure vessel industry, particularly its weldability, the effects of heat treatment on properties and its toughness. These characteristics are not part of the normal ASTM specification for the steel but are of concern to users. Many pressure vessel manufacturers and users had extensive experience with other structural steels with regard to such characteristics; but little comparable experience with A588 steels.

A great deal of the information that might be available about this type of steel is not in the open literature. This is because the A588 steels were originally developed as proprietary grades, that is, a number of steel companies developed and marketed steels in the A588 category prior to their inclusion in the ASTM A588 specification. Much of the information concerning their development and properties was, and is, proprietary and not available to the general public. As originally developed, these steels were to be used both for their corrosion resistance and their strength. Their particular weathering characteristics were such that, with time, they developed an adherent self-limiting oxide coating that allowed them to be used in some applications without painting. Indeed, they were marketed for many years under the general category of "weathering steels." This still represents a significant but not major portion of their market.

A larger portion of the original market came from the simple fact that the yield strength of these grades is 50 Ksi (345 MPa) minimum up to 4 in. (102 mm thick), which represents about a 30% increase over the normal A36 or other structural grades. When purchased for strength, as is common today, they are normally used in the painted condition.

To obtain material for this survey, it was necessary, not only to examine public data but also to request a variety of steel suppliers and users to pool their information in an anonymous manner. As a result, considerable additional information on the behavior of specific heats of A588 steel, and on a number of research projects undertaken by both steel suppliers and users to better understand these steels, was made available to the committee. The data obtained from the open literature is indicated in the bibliography. The emphasis in this report, however, is not the data available to the public but rather on that which is unpublished. It will be understood, then, that the information that has come from files of industrial sources will not be documented. In most cases the reason that these data have not been made public is that they relate to specific commercial product developments or specific structures and many involve more than one company.

A note of caution should be made when reviewing the data presented in this report. The subsequent sections will contain information on the mechanical properties, particularly strength and toughness, of the steels. There are a number of heats of this steel which are made only to a strength and ductility specification. As a result, the other mechanical properties of these heats may not be known, even to the steel supplier. There may be occasions when a steel supplier will sample, for example, the toughness of heats of A588 steel whether toughness has been specified or not. But there are a larger number of instances where the steel supplier will not measure the toughness of the steel for applications where toughness has not been specified and may not be significant. For this reason, the listing of the range of toughnesses for A588 steel heats found in this report probably does not represent the entire range of toughness for all A588 steel heats. It rather applies to those for which a minimum toughness may have been specified or for which the steel supplier has made toughness measurements for his own information. It would be misleading, therefore, to assume that heats of A588 could not have toughness values outside the envelope suggested in this report even though the data are extensive.

This decreases the value of the report to some extent, but is inherent in the data collection process. Perhaps a more useful aspect of this report is the way in which toughness, strength or other properties can be varied within the specifications of the grade by appropriate heat treatment or other processing rather than the data alone, which are admittedly incomplete.

A second limitation of this report is the small amount of information on structural shapes. These are an important product form for A588 steel but little data were available on them from the standpoint of either strength and toughness. Moreover, the pressure vessel users are generally more interested in plate properties, so shapes are not given special consideration. This does not necessarily mean the data developed for plates has no application to similar thickness structural shapes, however, the property data for shapes in this report are limited.

TYPICAL SPECIFIED COMPOSITIONS AND PROPERTIES

As indicated before, materials now under the ASTM A588 specification were a variety of commercial steels developed under proprietary trade names during the 1950's. As a result, when the A588 grade was created it was a multi-chemistry specification. The specific advantage the material was to provide over other constructional materials was higher yield strength and improved corrosion resistance. Thus, while other mechanical properties, such as ductility, were specified for the steel, it was strength and corrosion resistance that made it attractive. These two characteristics are still emphasized in the specification,(1) which is included as Appendix I to this report. The composition requirements in Table 1 of this specification illustrate the current multiple chemistry aspects of this material. Simultaneous achievement of strength and corrosion resistance has been left to the specific metallurgical philosophy of the sponsor of each grade, thus each steel company initially supplied one, or perhaps two, of the various grades in the specification.

The whole underlying philosophy was essentially an early use of the microalloying concept. By this it is meant that properties are achieved with a small amount of a number of alloying elements rather than a large amount of any one. The grades generally have high Mn content, some solid solution strengtheners such as Ni, Cr or Mo, which also serve to improve their corrosion resistance, and an alloy carbide strengthener such as V, Ti, Nb or a combination of them. Thus they were forerunners of the newer microalloyed steels that are being marketed extensively today. They differ from these newer steels in that the carbon content, while lower than many other typical constructional grades, is higher than utilized in a number of the most recent microalloyed steels.

Today, the proprietary lines separating many of these materials have become somewhat blurred and the most popular grades, A and B, may be purchased from a variety of suppliers. Indeed, although the specified chemistries for grades A and B differ in their limits, typical compositions are relatively close and when plates of these two grades of A588 are purchased it may be difficult to distinguish which of the two grades was intended. Almost all of the data in this report are for Grades A and B.

Strength properties of the A588 steels will generally exceed the required levels in Table 2 of the ASTM Specification (Appendix I) by a modest but definite increment since failure to meet the specification will result in rejection of material. Within this general statement, however, there is a variation in strength that depends primarily upon the thickness of the material and its heat treatment and this is reflected in the specification for plates. Figure 1 shows the strength variation for as-rolled A588 Grades A and B supplied by three different steel companies. It will be seen that while there is substantial variation in strength, suppliers have little difficulty in meeting minimum requirements. Examples of the strength properties of normalized A588 heats are seen in Figure 2. A588 is specifically made to fine grain practice and can be sold in the as-rolled or normalized condition. For most structural applications, it is sold in the as-rolled condition but when toughness requirements are specified it is often, but not necessarily, normalized. The implications of this practice with respect to unspecified properties, such as toughness, will be discussed later. With respect to strength, the use of normalizing practice usually at 1650°F (900°C) can reduce the yield strength so the increment in strength above the minimum level will be decreased. Indeed, it is possible if material is purchased in the as-rolled condition and subsequently normalized by the fabricator or user, the yield strength may fall below the minimum indicated in the specification. In practice this shortfall is rare, and when it does occur it is typically only 2 to 3 Ksi (14 to 21 MPa) and thus not significant in terms of service. Figure 3 shows research data illustrating this effect. A number of plates of A588 were normalized and their properties were compared to those of the as-rolled plates. As may be seen, for the same composition the normalized plates have lower strength but are more ductile. Since some of the material has yield and tensile strengths below the minimum for the grades, it would not be sold by the steel supplier at this strength level. The use of normalizing is generally associated with the attempt to improve impact toughness, and thus changes in strength and ductility are secondary factors.

Some heats of A588 steels may be quenched and tempered to provide assurance of minimum strength in heavier sections. Figure 4 shows some data for quenched and tempered A588 Grades A and B. The yield and tensile strengths appear to be generally higher than that of the as-rolled or normalized steels for equivalent section sizes, which for the quenched and tempered steels are generally greater than 3 inches.

The ductility requirements for the A588 steels are modest with respect to the typical capabilities of carbon-manganese or alloy steels of this type and suppliers do not normally have any difficulty meeting minimum specifications. Extensive data surveyed for this report but not included in the figures confirms this to be so. A limited amount of as-rolled and normalized plate data demonstrating typical ductility properties are seen on Figure 3. It may be noted that the ductility requirements, as seen in Table 2 of Appendix I, make special allowances for wide plates and heavier shapes.

As indicated above, property data for structural shapes are limited but some strength data for shapes are seen on Figure 5, plotted according to the thickness of the section (flange or web) from which the samples were taken. When compared to data for as-rolled plates, Figure 1, it appears that the yield and tensile strength range for the shapes is a little lower than for plates of equal thicknesses, although generally well above the minimum.

UNSPECIFIED PROPERTY TRENDS

Toughness

One of the more interesting aspects of the industry survey was the extent to which steel users looked to the A588 grades for properties which are not specified, the prime example being impact toughness. From the survey it was evident that many believe this grade to be superior in toughness to other structural steels even though a Charpy impact or other toughness specification had not been included with the order. Toughness was then an unspecified but expected mechanical property.

A survey of a large number of samples of A588 Grades A and B shows that the toughness of this material can vary widely. Figure 6 illustrates these variations in toughness for the as-rolled material. As seen in this figure, Charpy impact toughness is, in general, a function of thickness of the product but the toughness variation is exceedingly great. This implies that the toughness level achieved by a particular product can vary substantially unless a required level of toughness has been specified. A588 steels are not unique in this respect. Similar studies[2,3] on steel such as ASTM A36, the ABS grades, and other constructional grades show the same type of variation, particularly in the hot-rolled condition. As has been pointed out, the envelope of toughness shown here does not, in all probability, represent the total population of A588 steels. The heats shown on these figures are those for which toughness information was available, many of which were made to a minimum toughness specification for service in bridges. However it is believed by the investigator that the range seen here is typical of a large portion of the A588 materials available.

The most common toughness measure for the A588 steels has been the Charpy V-notch impact test. A small amount of data was also available from NDT drop weight tests. These data are shown in Table 1. The range of NDT temperatures shown are generally consistant with the 15 ft-lb transition temperatures shown for longitudinal as rolled plates in Figure 7.

A limited amount of toughness data on as-rolled shapes is seen in Figure 5. This shows the range of toughness for shapes is a little greater than for plates but the lower limits in toughness are about the same.

Also shown on Figure 6 are the effects of longitudinal vs. transverse property measurements and on Figure 7, the effect of normalizing heat treatment. Considerably less data are available for transverse properties or for normalized material than for the longitudinal as-rolled material. This is because transverse toughness properties are even more infrequently specified than toughness alone, and thus it is a rare occasion when a transverse toughness test is performed. From these figures it is clear that transverse toughness is significantly lower than longitudinal toughness and that transverse transition temperatures are much higher than their longitudinal counterparts because much of the A588 product is straight away rolled. Transverse transition temperatures of the as-rolled A588 steels are, on average, 35°F (19°C) higher than their longitudinal counterparts, although this can be quite variable. Figure 7 also shows a few instances in which the transverse transition temperatures are lower than the longitudinal values; these are, of course, the exception rather than the rule. Most of the data shown in Figure 7 are from the same heats of steel, that is to say, the transverse and longitudinal specimen data are taken from the same plate of steel at each thickness range and thus the results should be directly comparable.

A second and equally important effect, also seen in Figure 6, relates to the use of normalizing to improve the toughness of the A588 steels. The normalized steels typically have transition temperatures that are, on average, 100°F (66°C) lower than their as-rolled counterparts and have much higher shelf toughness. The A588 grades are, by specification, made to fine grain practice (Specification Section 4.2). Much confusion exists about what this specification means, especially among steel purchasers who may incorrectly associate this practice with good notch toughness. Fine grain practice means aluminum-silicon deoxidation, which can produce fine grain size when appropriate heat treatments are applied. If the steel is only hot rolled, the grain size is controlled primarily by the finishing temperature which can be quite variable. As a result, fine grain practice does not necessarily ensure that fine grain size will result. This is a point often misunderstood by users. As may be seen from Figure 6, good toughness can be found in as-rolled products under certain circumstances. However, if the full potential of the material is to be achieved, the normalizing heat treatment must be applied to give uniformly effective results.

The extent to which these last two variables can influence the toughness of an A588 steel is illustrated in the Charpy impact curves seen in Figure 8. These curves are taken from a study [4] of A588 and show longitudinal and transverse Charpy impact properties over a range of temperatures. Four conditions are illustrated: as-rolled longitudinal, as-rolled transverse, normalized longitudinal, and normalized transverse. A very substantial spread in properties is shown both in terms of transition temperature and in terms of upper shelf or maximum impact energy. The upper shelf energy is not revealed by the normal Charpy impact transition temperature shift data seen in Figure 7 but is a significant factor in the difference between the longitudinal and transverse mechanical properties of the steels and between the as-rolled and normalized conditions. This is not to imply that the differences in toughness between as-rolled and normalized material or between longitudinal and transverse mechanical properties are only seen in A588 steels. It can be easily demonstrated from surveys of carbon-manganese steels that similar effects occur for most constructional steels especially those that are not cross rolled extensively. The traditional methods of only testing longitudinal impact specimens or leaving toughness unspecified simply does not reveal these differences.

Many carbon-manganese and low-alloy steels do not have extensive cross-rolling and will have significant differences in mechanical properties between the longitudinal and transverse orientations. The differences in toughness between the normalized and the as-rolled material seen in the A588 grades do not necessarily apply to all low alloy or carbon manganese steels, however, because they depend upon the de-oxidation practice. Materials not made to fine grain practice may show less improvement as a result of normalizing, depending upon other circumstances. From a practical viewpoint, good impact toughness in a grade such as A588 may not be best achieved by specifying a <u>heat treatment</u> to be applied to the material but rather by specifying a <u>toughness level</u> required for service. That is, toughness should be transferred from the unspecified category into the specified category.

Fabrication Effects on Toughness

Even if toughness is a specified property, it is possible that the toughness of the material can be altered by treatments applied by the fabricator. Thus even if initial toughness is known, the toughness of the final product may yet be unknown. Two common fabrication processes alter the toughness of the material; mechanical forming and welding. The effects of welding will be dealt with later. With respect to mechanical forming, there is an increasing body of evidence that shows that some carbon-manganese and microalloyed steels given mechanical forming operations, with or without subsequent heat treatment, can experience losses in impact toughness. The nature of these toughness changes is illustrated in Figure 9, which shows the changes in impact transition temperature with mechanical forming, subsequent aging and post-aging stress relief treatments for A588 Grade B from studies performed at Lehigh University.[(2)] Studies on other heats of A588 steels, which are shown on Table 2, give similar results. The range of strain in mechanical forming in these studies lies within that undertaken by many fabricators. Tensile strains of from 2 to 3% increased transition temperatures from 9 to 80°F (5 to 44°C), while 5% strain increased transition temperatures from 18 to 83°F (10 to 46°C). Strains in the 10% range increased transition temperatures from 22 to 115°F (-5 to 46°C). Both normalized and as-rolled steels are effected.

As Figure 9 shows, the effects of strain are exacerbated by aging. Aging was done at (260°C) 500°F, a temperature intended to produce maximum strain aging effects. The large initial difference between the normalized and as-rolled materials, described previously, is also evident in Figure 9. The most significant effect, however, is the loss of toughness, as a result of cold deformation and subsequent aging.

It has often been assumed that the effects of mechanical strain can be eliminated by post-strain stress relief treatments in an appropriate temperature range. However, it is seen in Figure 9 that the A588 grades do not necessarily respond to this treatment in a temperature range usually employed for the purpose. It has been found that stress relieving alone can reduce the impact toughness of A588 steels by shifting their transition temperature. This fact can be confirmed by a number of studies both at Lehigh University[(5)] and elsewhere on some microalloyed carbon-manganese and low alloy steels, including A588. Toughness loss can be progressive with holding in the stress relieving temperature range. At the present time, the exact cause for this phenomena is not fully known, however, it does appear that at least some of the loss is associated with the formation of arrays of carbides on grain boundaries during stress relieving.

The loss of toughness from these straining and aging treatments is particularly significant when materials have low initial impact toughness. That is, materials that were received in the as-rolled condition and for which no toughness was specified. Under these conditions material which had toughness generally adequate for service may have it reduced below some minimum required for the application. Utilizing a normalized or toughness specified material for such an application will not eliminate the effects of straining, aging and stress relieving, but could provide material that was sufficiently tough that subsequent losses would not put the steel into a critical toughness range in the service regime.

Fracture Toughness

A mechanical property of great interest in recent years, both in structural steels in general and A588 steels in particular, is K_{Ic} fracture toughness. This is both an unspecified and, at present, a generally unspecifiable property for these steels. The measurement of K_{Ic} toughness in static tests of A588 steel is difficult because of its high toughness in the ambient temperature range. Investigators have approached this problem in many ways in the last 15 years, most recently using either J_{Ic} or CTOD characterizations. Data of this type are still scarce, and even the significance of some of the older data that does exist, while obtained using the best techniques of the day, is now open to debate.

With this limitation in mind, tests at Lehigh from a number of investigations have resulted in a small body of K_{Ic} data for A588 grades A and B, and these data are presented in Figure 10. The data are from plates and shapes 1.5 to 2 in. (38 to 51 mm) in section thickness and are for as-rolled material. Both static and dynamic data are represented. As might be expected, there is a wide range of scatter which may be due to testing technique or inherent in the material. A line representing the lower bound for the data has been constructed that provides what the investigator believes is a conservative estimate of K_{Ic}. The lower bound is seen to be constant over a wide temperature range and then begins to rise sharply at about 0°F (-18°C). The dynamic data are more limited and do not rise in the temperature range covered. This is in keeping with the normal relationship between static and dynamic testing which would predict an increase in dynamic toughness about 140°F (60°C) above that of the static curve, or well above room temperature. This is also consistant with the Charpy impact data for as-rolled A588 seen in Figures 6 and 8.

Fatique Resistance

Another property for which there may be expectations that are not realized is high cycle fatigue resistance. The higher yield strength and somewhat higher tensile strength of the A588 grades may be equated with the improved fatigue resistance in welded construction. While the principle relating tensile properties to fatigue resistance is certainly true in small machined components, it is not true in most forms of welded construction. This is because fatigue resistance in this case is controlled by the presence of defects introduced during welding and by residual stresses and stress concentrations inherent in the design of weldments. Expectations of improved fatigue resistance may turn out to be not realized in the actual weldments.

SPECIAL PROCESSING

A number of special processing options are available to purchasers of A588 Steel that should be mentioned here. These options include both heat treatments and special processing to control inclusion size, shape and distribution, and lead to improved mechanical properties. The use of normalizing has already been discussed and illustrated as has the effect of quenching and tempering. It has been demonstrated over a number of years that quenching and tempering can improve the mechanical properties of some products, particularly low alloy steels,[6] and it has also been demonstrated that this heat treatment can result in improved strength in A588 steel (Figure 4). As has already been shown, normalizing also produces substantial improvements in toughness. Quenching and tempering is more rarely done for this steel, and usually only to improve strength. Figure 11 shows some data comparing normalized and quenched and tempered A588 with respect to toughness. The improvements in toughness shown in Figure 9 are marginal over those obtained by simple normalizing because the aim of this treatment is not improved toughness, and tempering temperatures are selected accordingly..

Special processing to control inclusion size, shape, and distribution can also prove beneficial to A588 steels. Under unfavorable circumstances, all constructional steels may be sensitive to the problems associated with low through-thickness ductility. One example of this is the occurrence of lamellar tearing during welding. This problem is not a result of material properties alone, but is also a function of design of the welded joint, the level of restraint during welding, and the weld parameters chosen. With respect to through-thickness properties, it is possible, through special shape-control processing to reduce the number of inclusions present in the steel and to render their shape more favorable to through-thickness ductility. These treatments result in reductions in phosphorus and sulfur to low levels, less than .010%, and changes the composition of the inclusions to make them less susceptible to elongation and flattening during the plate rolling process.

The effects of such treatment on A588, designated in this case CaT for calcium treated, are shown in Figure 12.[7] As may be seen from this figure, although one of the important differences between conventionally treated and specially treated A588 is in terms of through-thickness ductility, all ductile behavior properties of the steel, including impact shelf toughness are significantly improved. Other properties, such as strength will not be improved. With respect to fatigue crack initiation, calcium treatment will improve fatigue initiation behavior and retard growth at and above ΔK values of 25 ksi$\sqrt{\text{in.}}$ (28 MPa$\sqrt{\text{m}}$). In the final stages of fatigue crack growth, in which fracture properties play a significant role, special processing to control inclusion size and shape will also be of benefit.

WELDING AND WELDABILITY

The welding of A588 steel does not differ significantly from that of other conventional steels with the exception that A588 grades may have somewhat higher hardenability than simple carbon manganese grades and if not recognized, this may cause difficulties with hydrogen-induced cold cracking. Most constructional codes, such as the American Welding Society Code D 1.1, recognize this to be the case and require the use of low hydrogen consumables in the welding of A588. Preheat requirements are also established for it as shown in Table 3. When welding difficulties are encountered with this steel, particularly in relation to hydrogen-induced cracking, a common cause is failure of fabricators to recognize that the requirements in various codes for this steel are a necessity for sound weldments, not just a desirable option. With some other grades of carbon-manganese steel stated requirements with respect to cleanliness, preheat and consumable control may be relaxed to some degree but not with A588 steel and its moderately higher hardenability. Limited laboratory data on several heats of A588 steels confirm the preheat values of Table 3 to be realistic.

These requirements are relatively modest compared to some pressure vessel steels and the welding of this material should be able to be accomplished without difficulty. Indeed weldability tests performed on A588 grade B at Lehigh University show it to be relatively resistant to hydrogen-induced cracking provided minimal requirements are observed.[8]

There are no particular problems with this material with respect to hot microcracking and it appears to be similar to other carbon-manganese constructional steels in this respect. Manganese content of the A588 steels is always relatively high and thus a favorable manganese to sulfur ratio results, which tends to limit hot cracking. Minimum preheat requirements have been established by steel suppliers for the cutting of A588 steels and these should be observed.

Welding consumables used for A588 steels are those employed for other constructional steels. When special toughness requirements are necessary in weld metals, a wide variety of commercial consumables are available. The only additional requirement placed on consumables are in those applications where weathering characteristics of the steel are to be maintained. Under these conditions, the welding consumables selected must be ones that can provide an oxidation color that will match the base material and steel and consumable suppliers can recommend weld metals which will meet this requirement.

One of the most common questions raised about the welding of A588 and other constructional steels has been concerned with heat affected zone properties. General experience with the heat affected zone properties of A588, particularly the coarse grained heat affected zone, has been favorable with respect to strength and toughness. Recent studies performed at Lehigh University[4] show that, over a wide range of heat inputs, the heat affected zone properties of A588 are at least as good as the as-rolled plate material and often as good as normalized material with respect to toughness. These data are shown in Figure 13 (and also Figure 10, which has one HAZ point). When low heat inputs are used, a relatively hard heat affected zone may result, as shown in Figure 14, resulting in some concern about heat affected zone toughness. However, heat inputs more typical of construction welding produced heat affected zones of acceptable toughness. Information available from industry sources, Table 4 , seems to confirm this.

Table 4 covers A588 plates with a range of thicknesses joined by shielded metal arc and submerged arc welds. It will be observed that for all but two welds (in the same steel), HAZ toughness exceed that of the base plate. The fusion line region in these studies appeared to have a lower toughness than either the plate or HAZ, althouth this result was not uniform. The role of vanadium in A588 in reducing HAZ toughness either before or after post weld heat treatment has been explored but no conclusive results are reported. The behavior of the HAZ for the steels in Table 4 bears no relationship to their vanadium or other microalloy contents.

Post-weld heat treatment of welded joints, however, commonly applied to reduce residual stress and improve the toughness of the heat affected zone, may not have a beneficial effect on the toughness of the weldment. Figure 15 shows data taken from the study at Lehigh University[4] illustrating this point. It will be seen that little improvement in toughness was achieved through post weld heat treatment and indeed some loss in toughness was recorded for specific cases. This experience is also matched by that of industry. Thus post weld heat treatment of weldments of A588 steels, as for some other microalloyed steels, ought to be carefully considered to determine if that treatment will perform a beneficial function overall.

SUMMARY

The increasing use of ASTM A588 steels for a variety of pressure vessel industry applications demonstrates a recognition on the part of steel users of the potential strength and other benefits of these grades. Steel suppliers can meet specified mechanical properties in light and heavy sections. However, A588 steels may have a range of properties depending on the options exercised by steel purchaser and specifications given to the steel supplier. Many purchasers look to the A588 steels for good strength with high levels of toughness even when toughness is left unspecified. This survey demonstrated that good strength and high toughness can be achieved in these grades but toughness levels no better than ordinary carbon-manganese steels can be expected unless toughness requirements are specified. Heat treatment can improve toughness and other ductility related properties and special processing may also improve lamellar tearing resistance and fatigue crack initiation and propagation properties. These options need to be considered by purchasers and fabricators when specific applications require them.

Mechanical forming of the A588 steel may result in losses in toughness, and stress relief treatments may not fully recover this loss. Welding of these steels is not difficult and weld metals with properties compatible with the base plates are available. Weld heat affected zones are satisfactory in strength and toughness over a wide range of heat inputs in the as welded condition. Toughness is not necessarily improved by post weld heat treatment. Since the A588 steels are somewhat higher in hardenability than many carbon-manganese steels, careful control of welding consumables and welding procedures is necessary to prevent HAZ hydrogen induced cold cracking.

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TABLE 1

NDT TEMPERATURE DATA FOR A588 STEELS (AS ROLLED)

Steel Code	Thickness mm (in.)	Yield Strength MPa	ksi	NDT Temperature[1] °C	(°F)
A	25 (1.0)	431	(63)	-45	(-49)
B	38 (1.5)	435	(63)	-10	(14)
C	50 (2.0)	384	(56)	-25	(-13)[2]
D	50 (2.0)	390	(56)	-15	(-5)[2]

[1] Longitudinal orientation.

[2] Flange in rolled shape, all others plated.

TABLE 2

STRAIN AGING EFFECTS IN A588 STEEL, GRADES A & B

Steel Code Thickness (in.)(mm) and Heat Treatment	Base 50% Shear Transition Temperature°F (°C)	Shift in Longitudinal 50% Shear Transition Temperature °F (°C) after 3%	5%	10% strain
1. 2.00 (52) - N	-58 (-50)	+36*(+20)	+50 (+28)	- (-)
2. 0.75 (19) - AR	-22 (-30)	+50 (+28)	+58 (+32)	+76 (+42)
3. 1.00 (25) - AR	-38 (-39)	+22 (+12)	+31 (+17)	+44 (+24)
4. 1.00 (25) - AR	-76 (-60)	+9 (+5)	+54 (+30)	+108 (+160)
5. 0.63 (16) - AR	-44 (-42)	+13 (+7)	+25 (+14)	+43 (+24)
6. 0.87 (22) - AR	-62 (52)	+11 (+6)	+18 (+10)	+22 (+12)

*2% strain only

N=Normalized
AR=As Rolled

TABLE 3

American Welding Society Preheat Temperatures[1] for Welding A588 Steel - AWS D1.1-85 Table 4.2

Material Thickness in. (mm)	Preheat Temperature °F (°C)
up to .75 (up to 19)	none
.75 to 1.5 (19-38)	50 (10)
1.5 to 2.5 (38-64)	150 (66)
2.5 and up (64 and up)	225 (107)

[1] These are also required minimum interpass temperatures

TABLE 4

Heat Affected Zone Toughness of A588 Steel Grades A & B

Steel Code &	Thickness - in.(mm)	Heat Input kJ/in (kJ/mm)	50% Shear Transition Temperature °F (°C) Base Metal	Fusion Line	HAZ
		SHIELDED METAL ARC WELDS			
1	1.0 (25)	50 (2)	-60 (-51)	-69 (-56)	-27 (-33)
1	1.0 (25)	50 (2)	-60 (-51)	-80 (-62)	-112 (-80)
2	1.0 (25)	75 (3)	-72 (-58)	-11 (-24)	+3 (-16)
3	2.75 (70)	70-100 (2.7-4)	-33 (-36)	+14 (-8)	-45 (-43)
4	3.37 (85.6)	55-105 (2.1-4.1)	-40 (-40)	- (-)	-45 (-43)
		SUBMERGED ARC WELDS			
1	1.0 (25)	100 (3.9)	-60 (-50)	-13 (-25)	-98 (-87)
2	1.0 (25)	125 (4.9)	-72 (-58)	-9 (-24)	-11 (-24)
4	3.37 (85.6)	63 (2.5)	-40 (-40)	- (-)	-44 (-42)

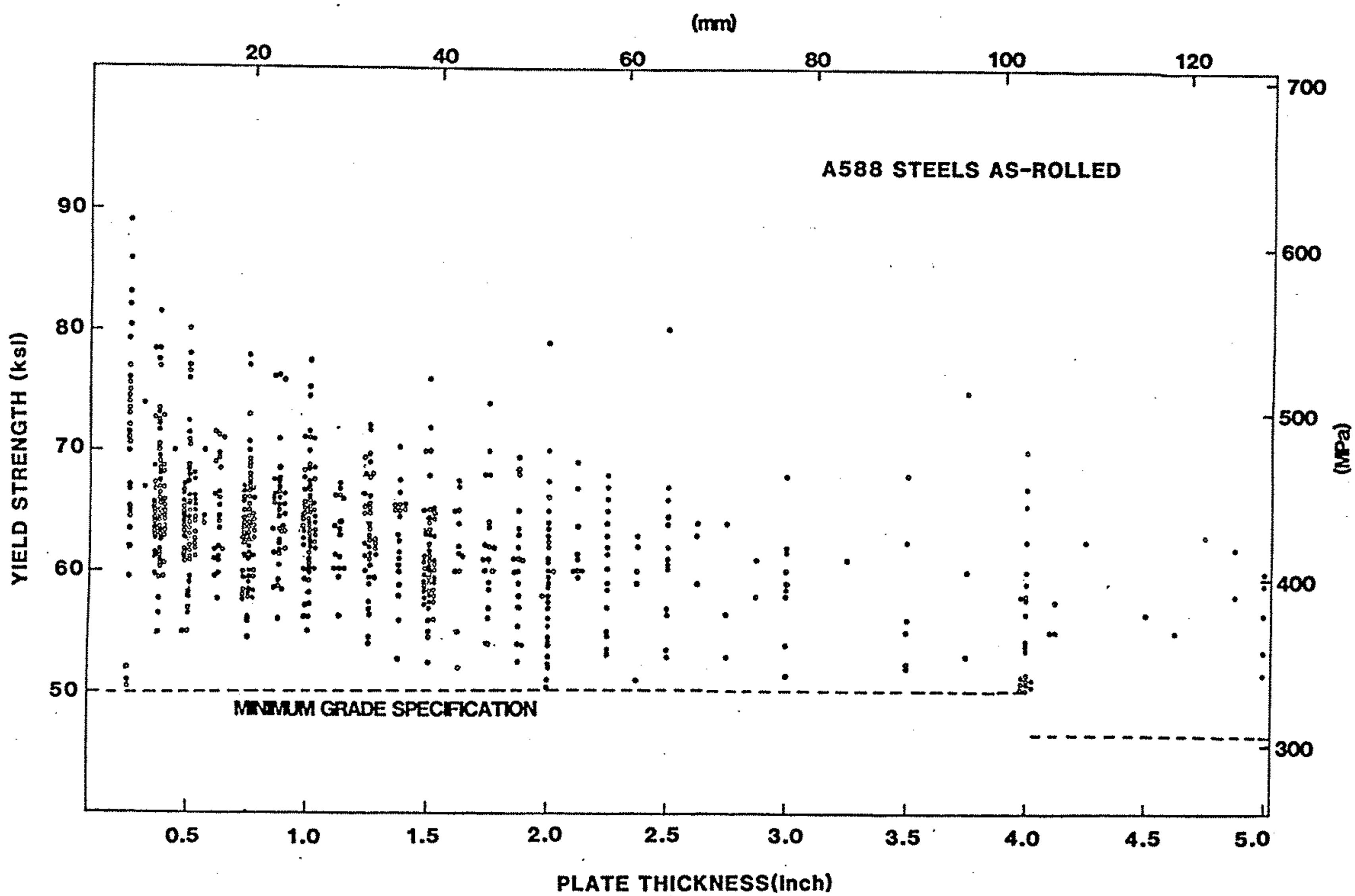


Figure 1a. Yield Strength Data for A588 Grades A and B.

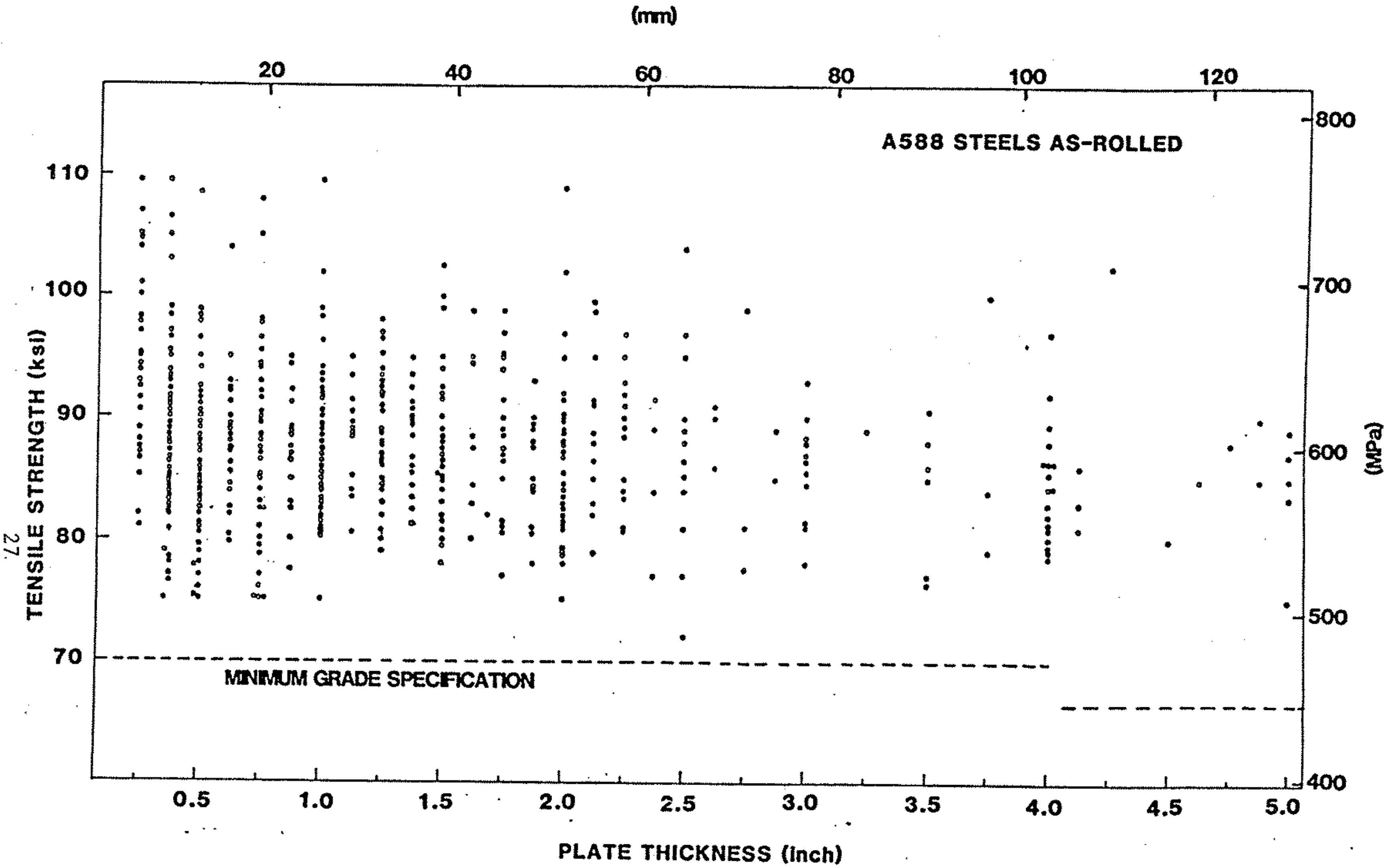


Figure 1b. Tensile Strength Data for A588 Grades A and B.

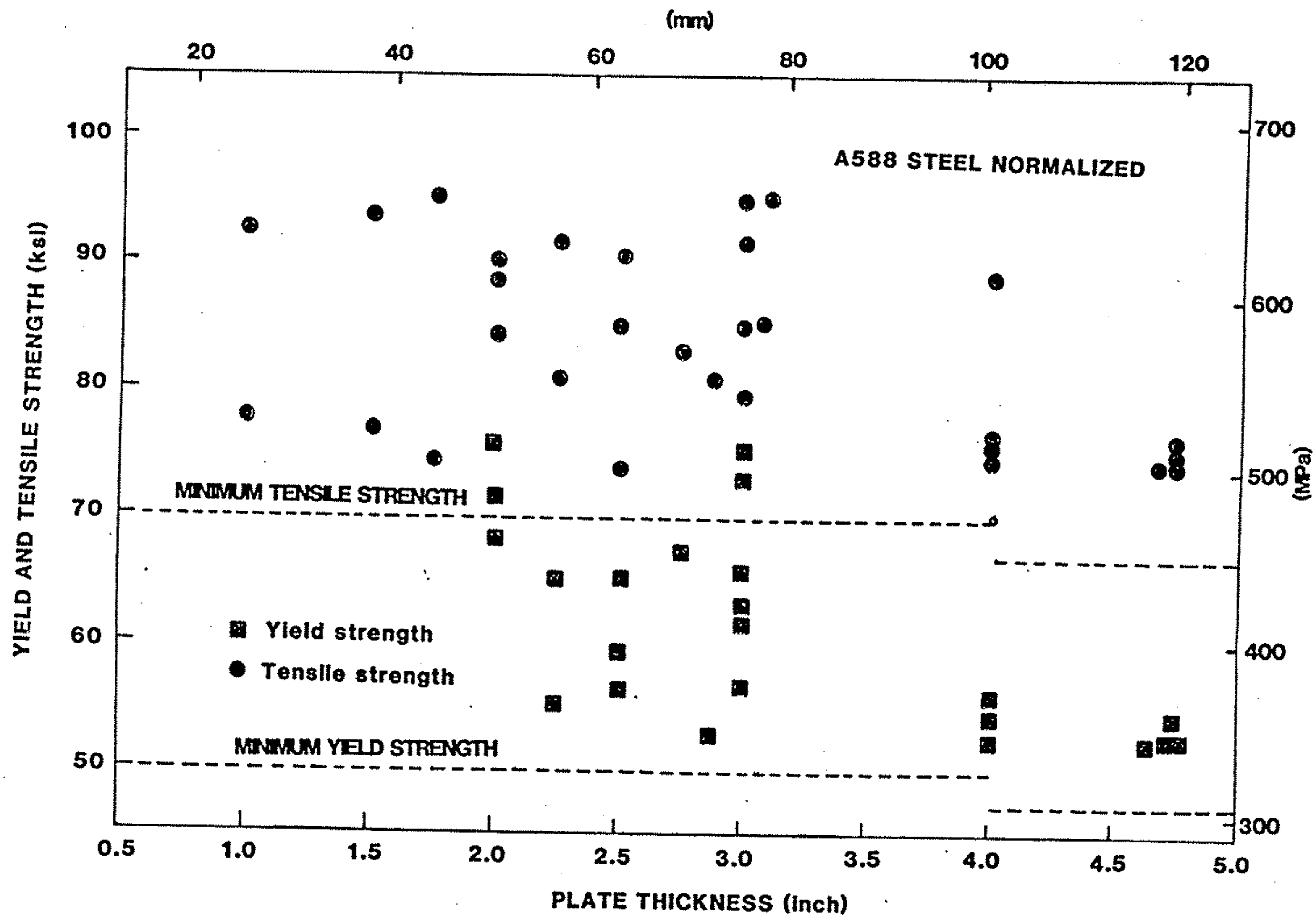


Figure 2. Yield and Tensile Strength Data for Normalized A588 Grades A and B.

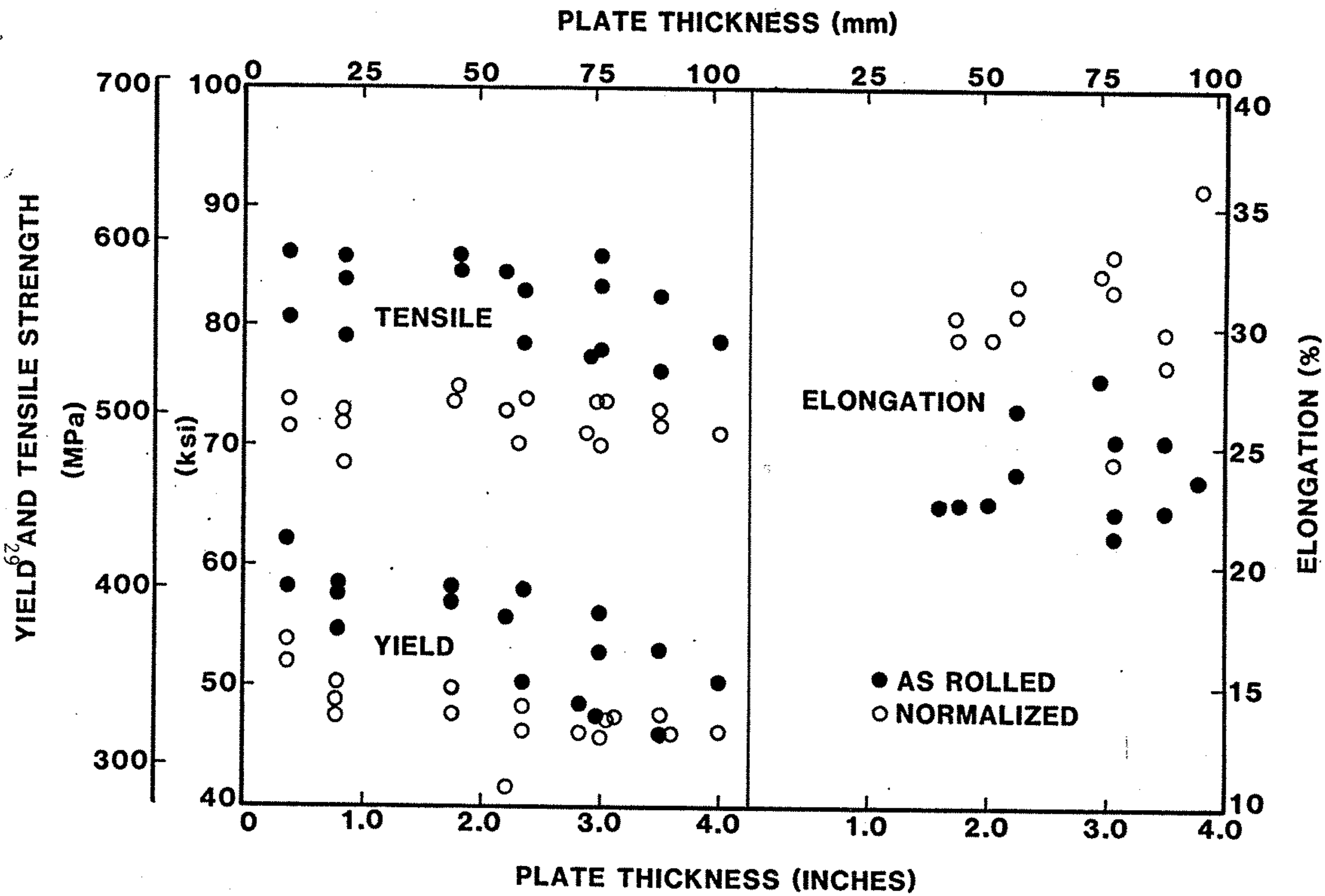


Figure 3. Strength and Ductility Data for A588 Grades A and B As Rolled and After Being Given A Normalizing Heat Treatment.

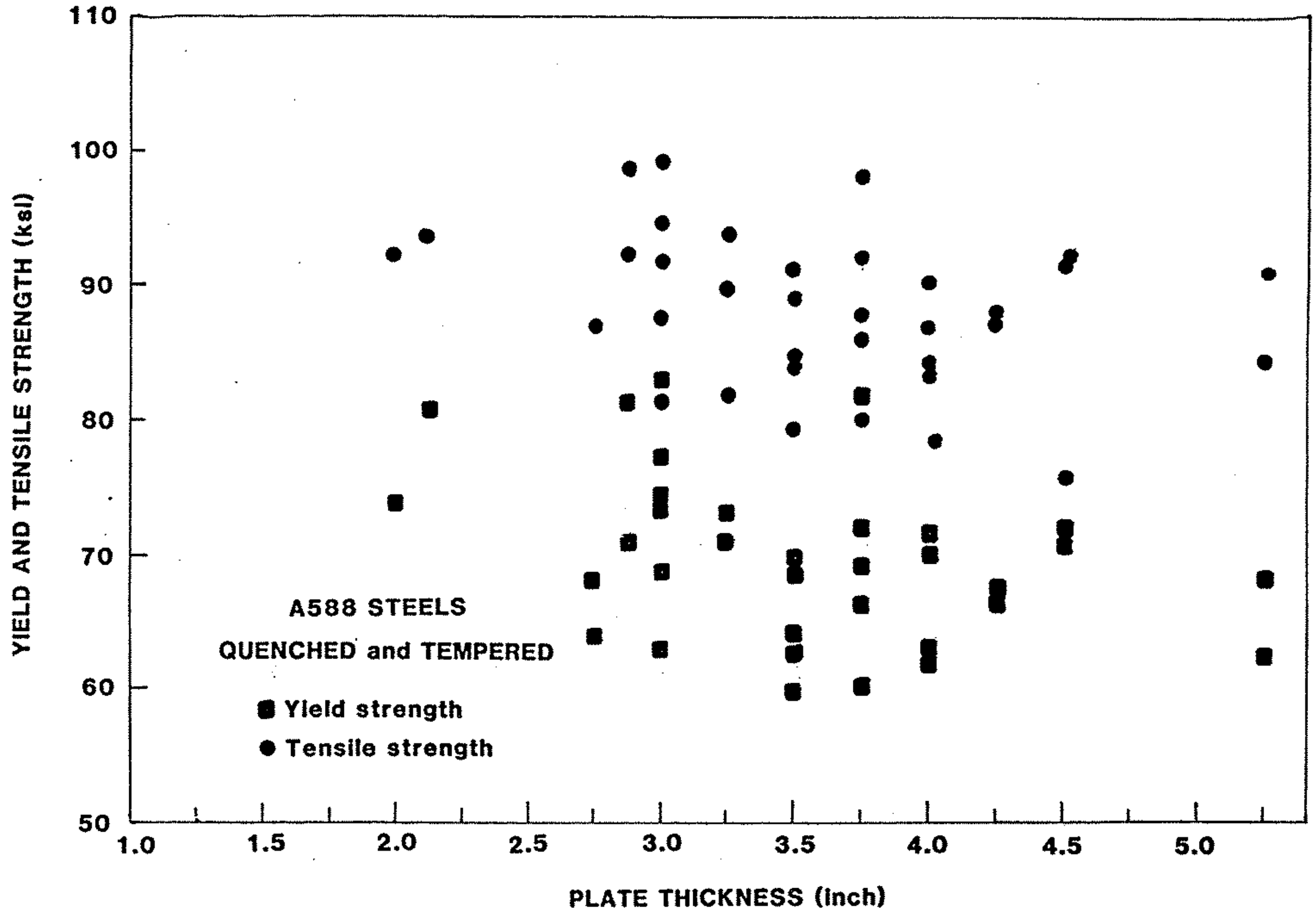


Figure 4. Yield and Tensile Strength Data for Quenched and Tempered A588 Grades A and B.

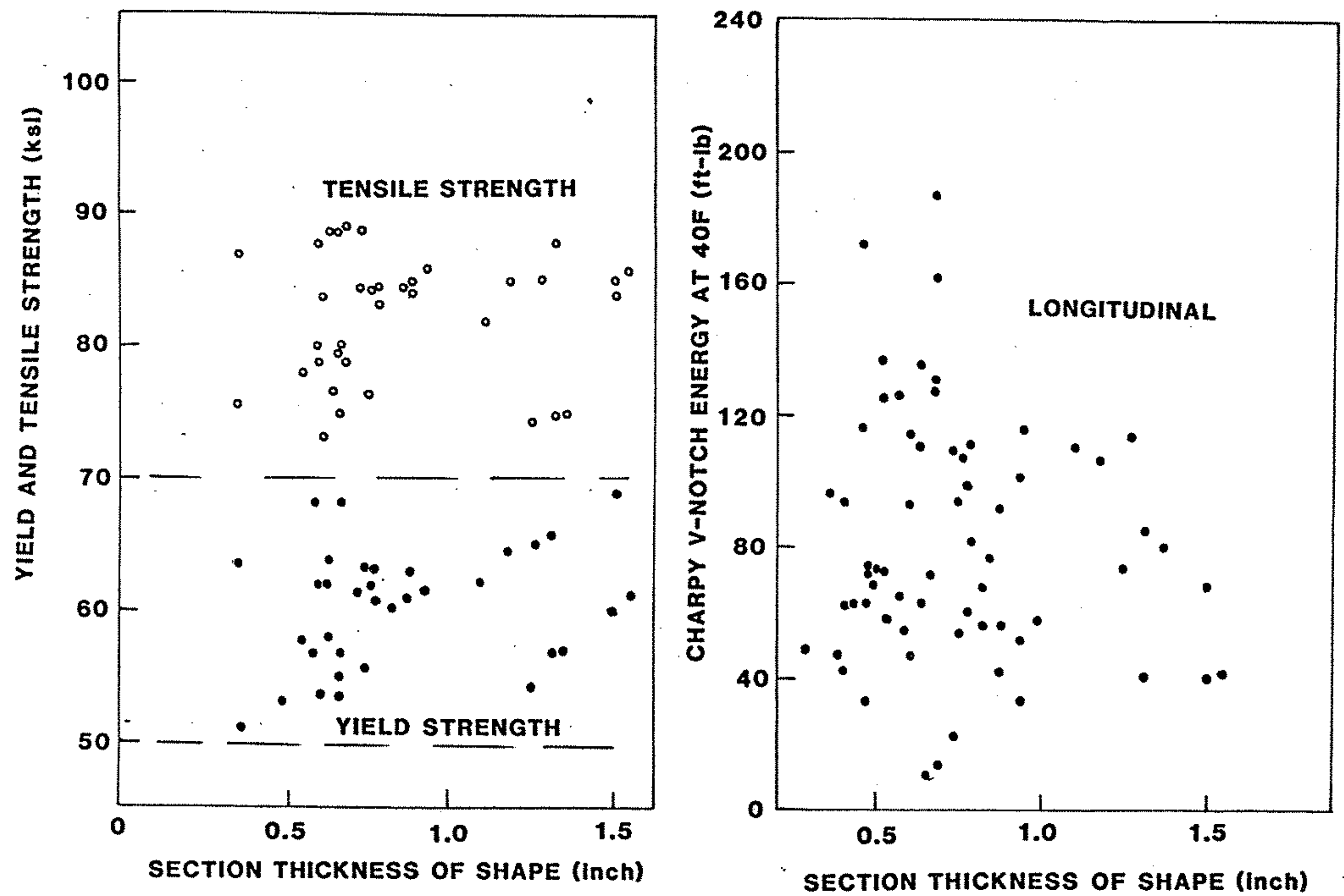


Figure 5. Strength and Toughness Data for Structural Shapes of A588 Grades A. and B.

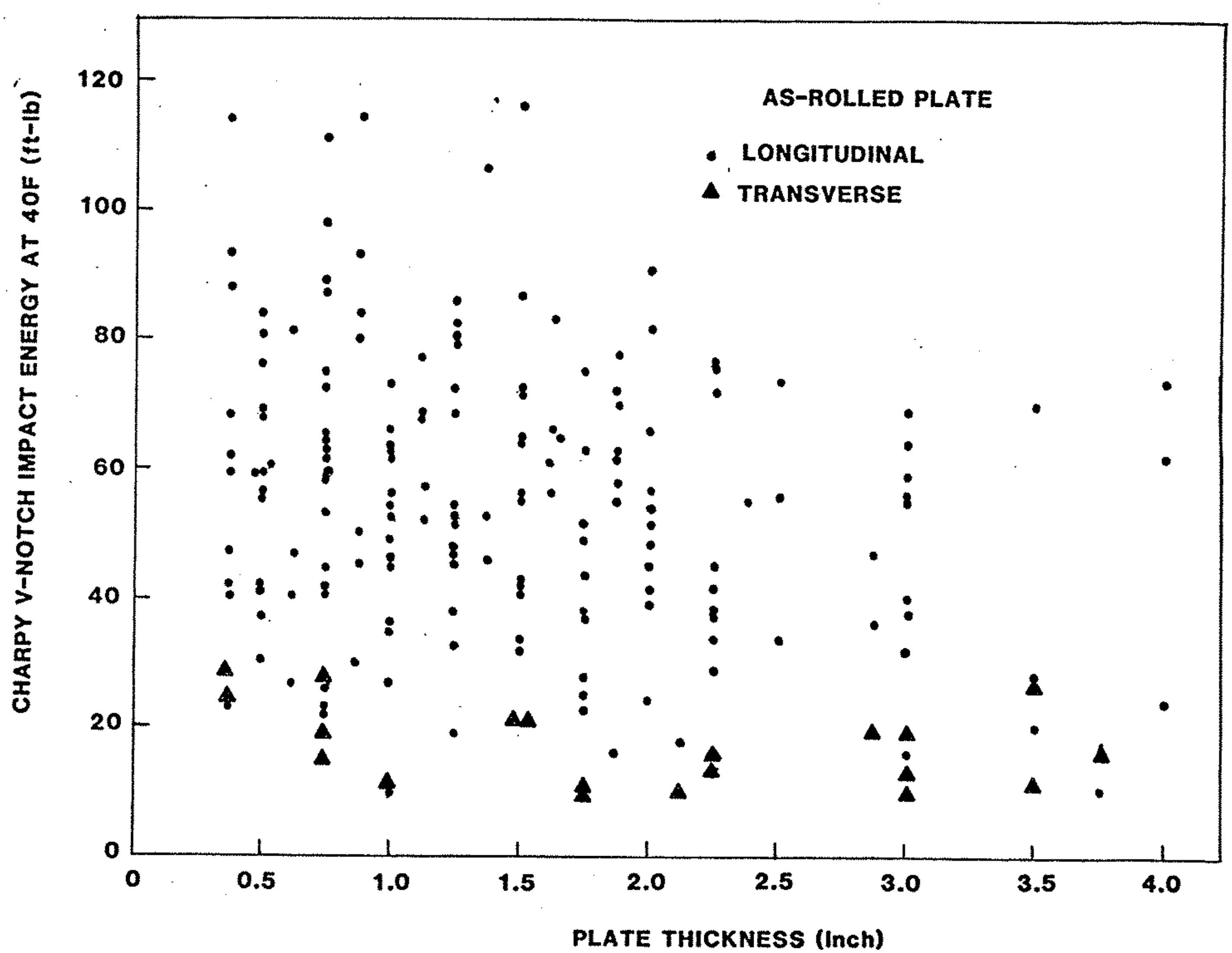


Figure 6. Charpy V-Notch Impact Toughness for A588 Grades A and B.

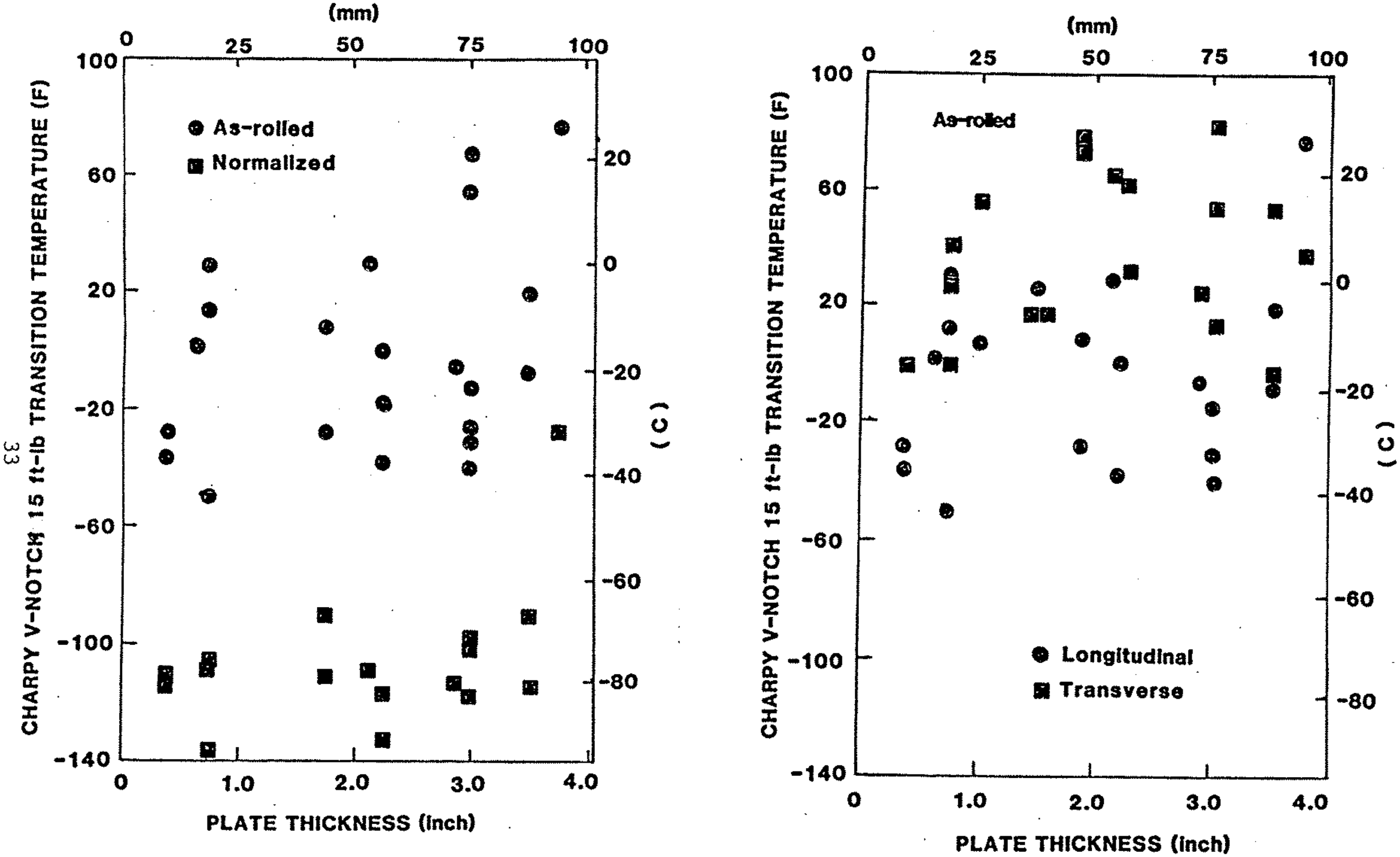
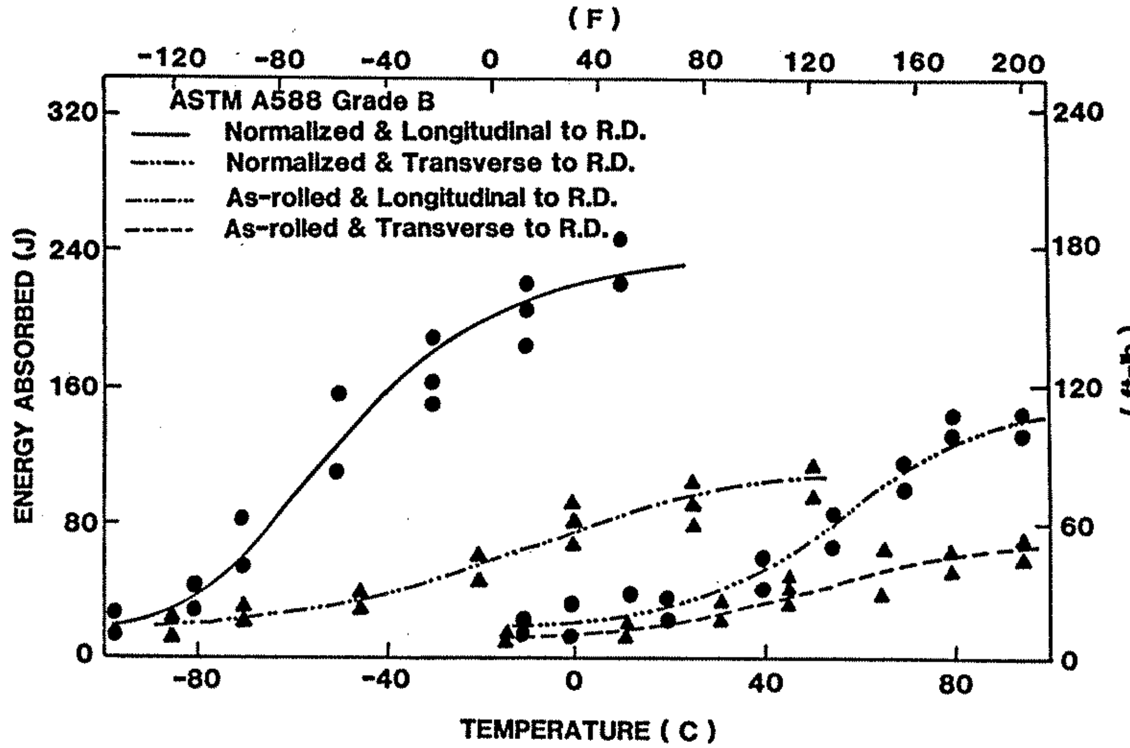


Figure 7. Charpy V-Notch Transition Temperatures for As Rolled and Normalized A588 Grades A and B.



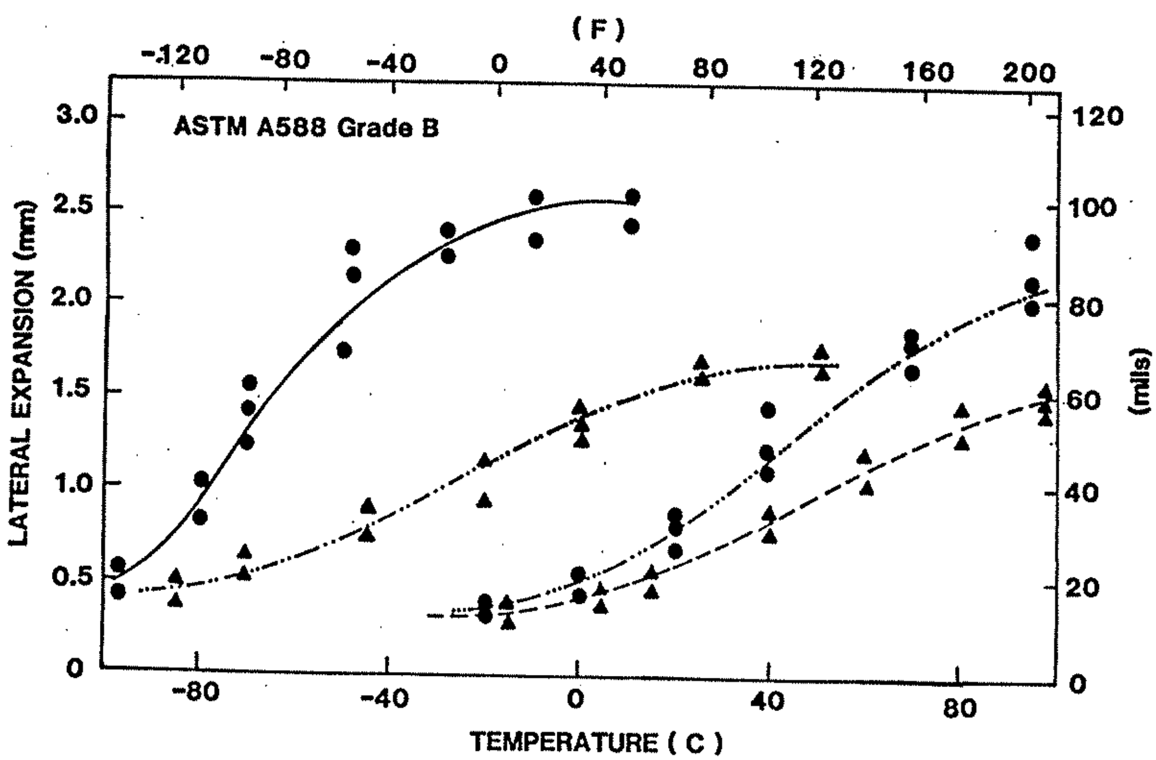


Figure 8. Effect of heat treatment and orientation on the Charpy impact toughness of A588 Grade B.

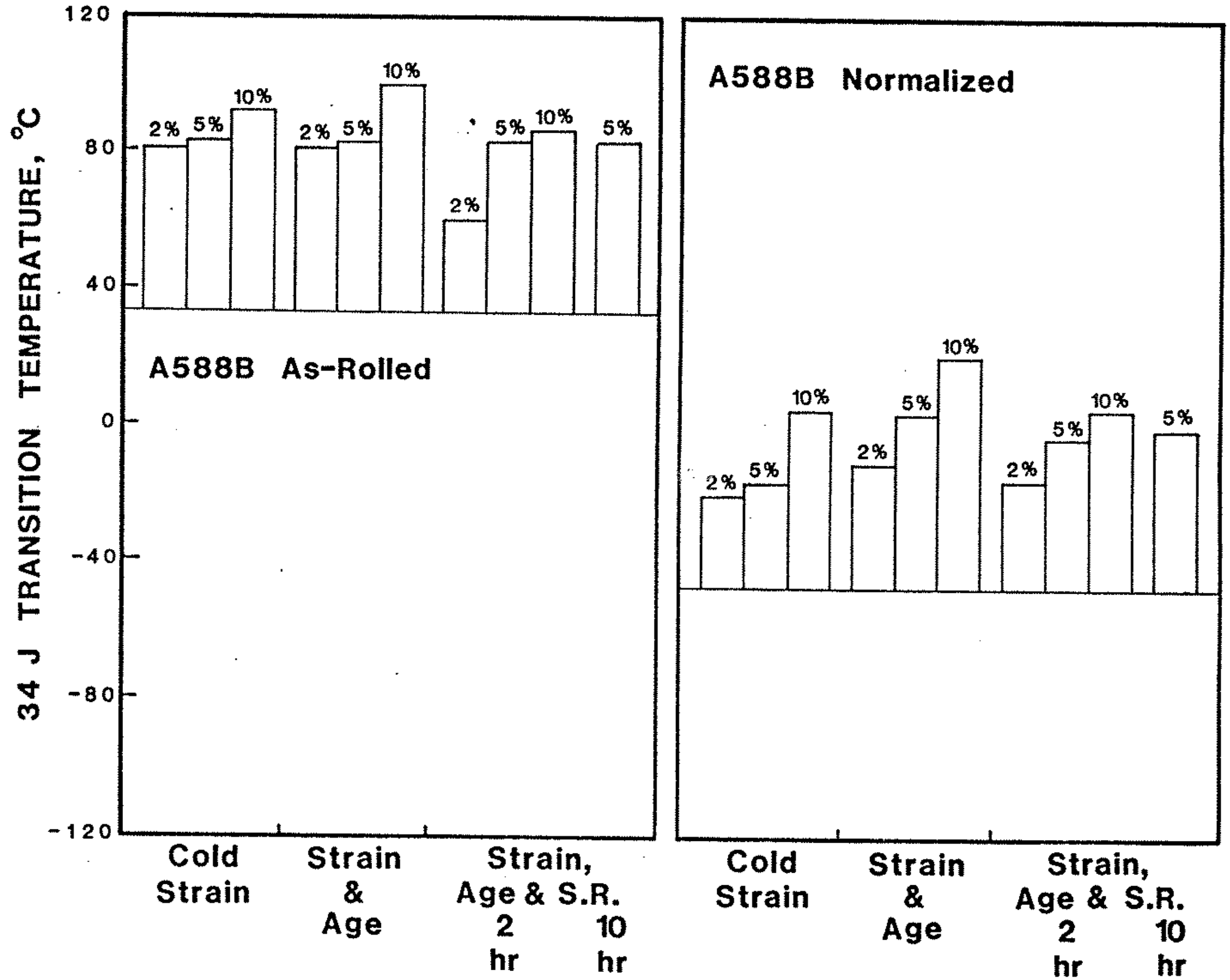


FIGURE 9. The effect of straining, aging and stress relief on the impact toughness of A588 grade B steel.

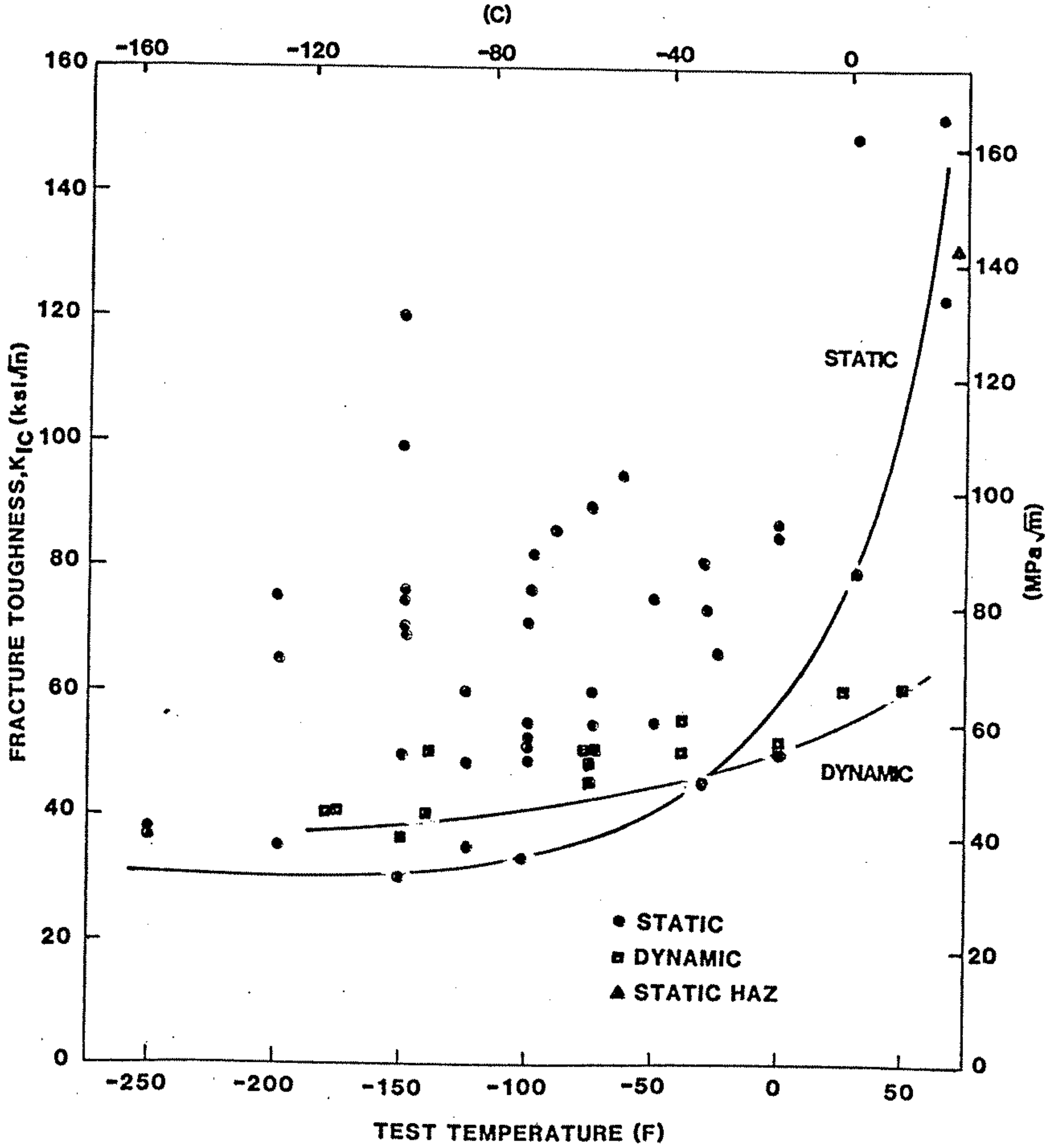


Figure 10. Fracture Toughness Data for A588 Grades A and B.

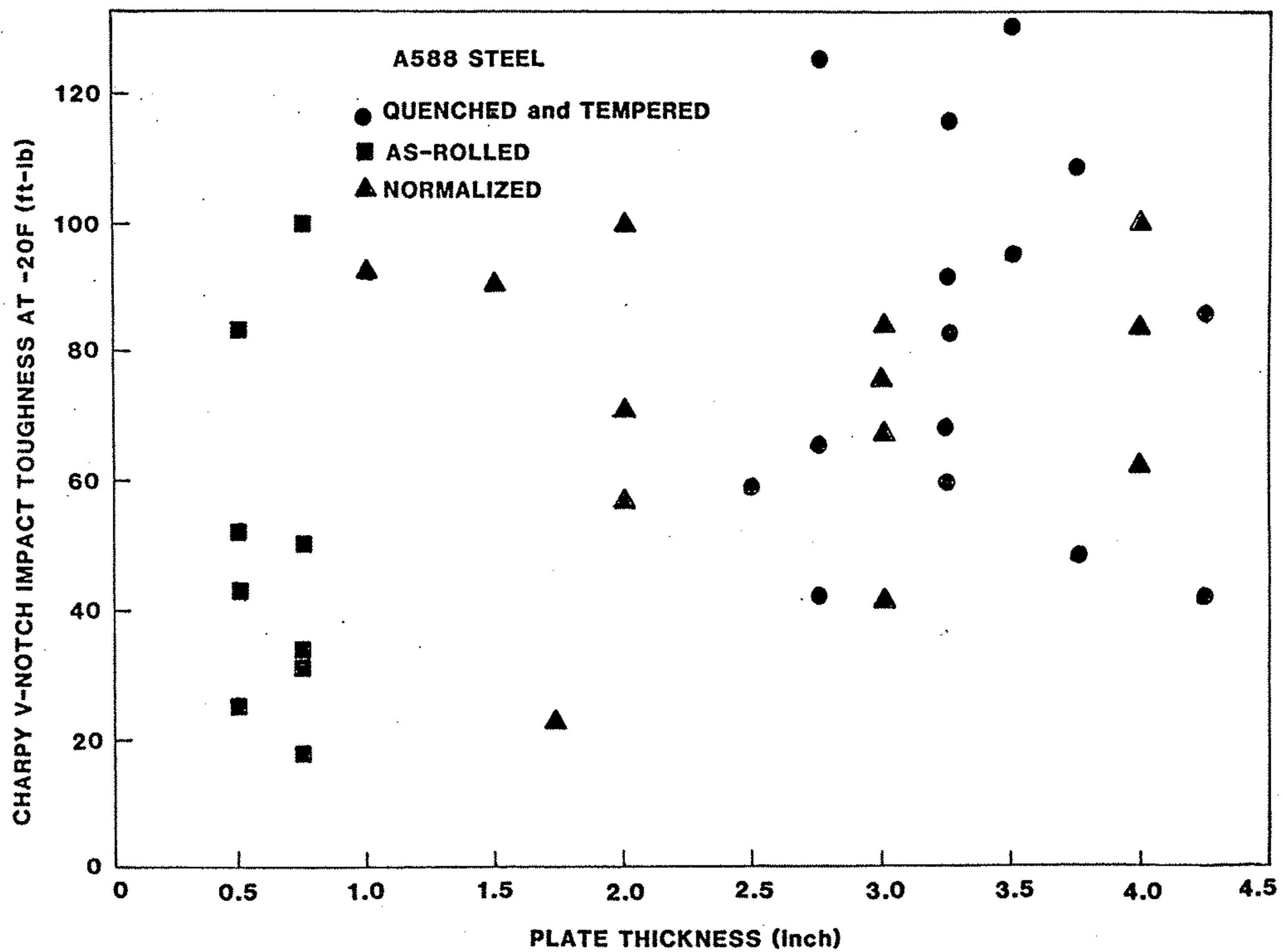


Figure 11. Charpy V-Notch impact Toughness for As-rolled, Normalized and Quenched and Tempered A588 Grades A and B.

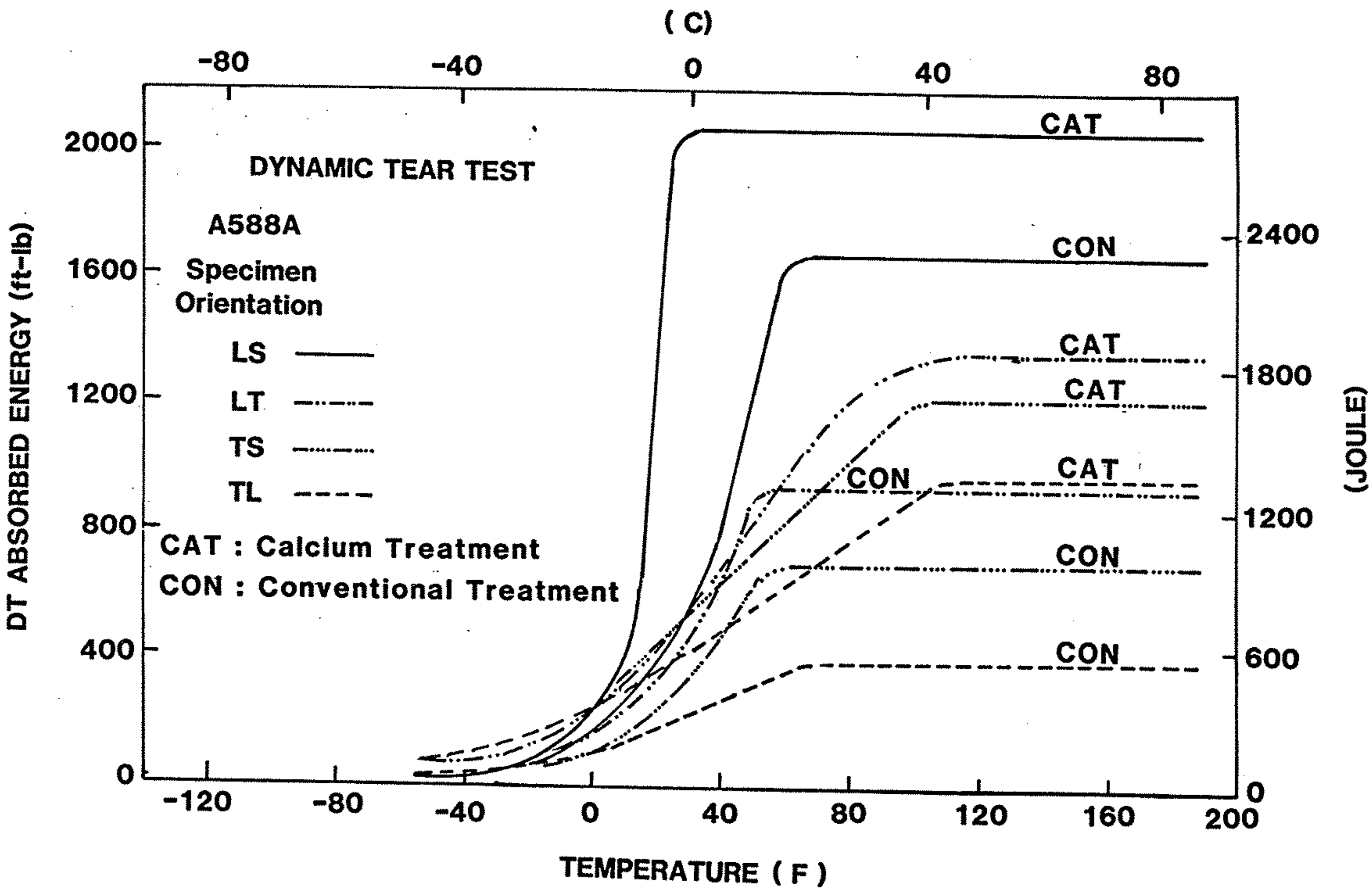


Figure 12. The effect of special processing on the dynamic tear toughness of A588 Grade A steel.

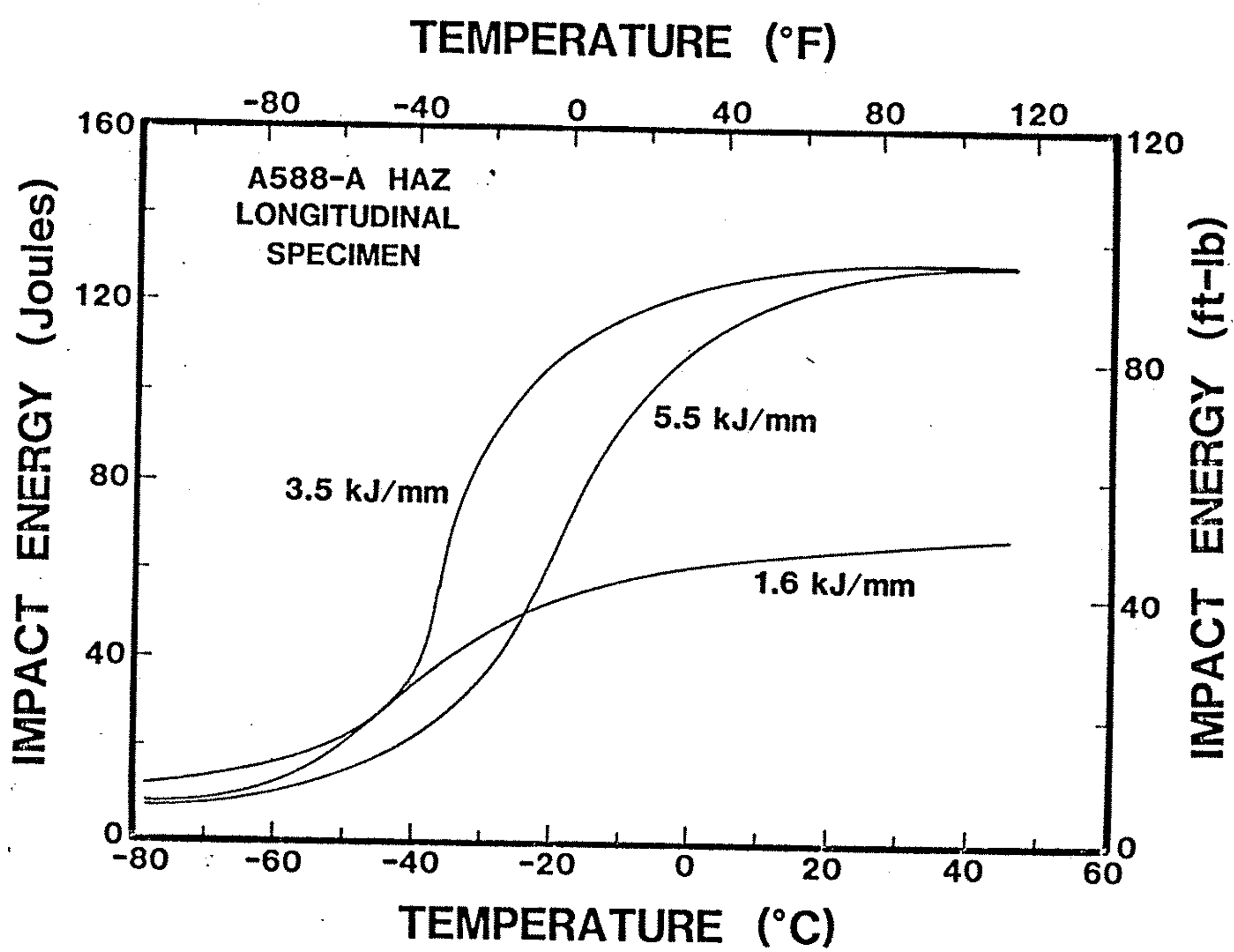


FIGURE 13. The effect of heat input on the toughness of the heat affected zone of A588 Grade A steel (normalized).

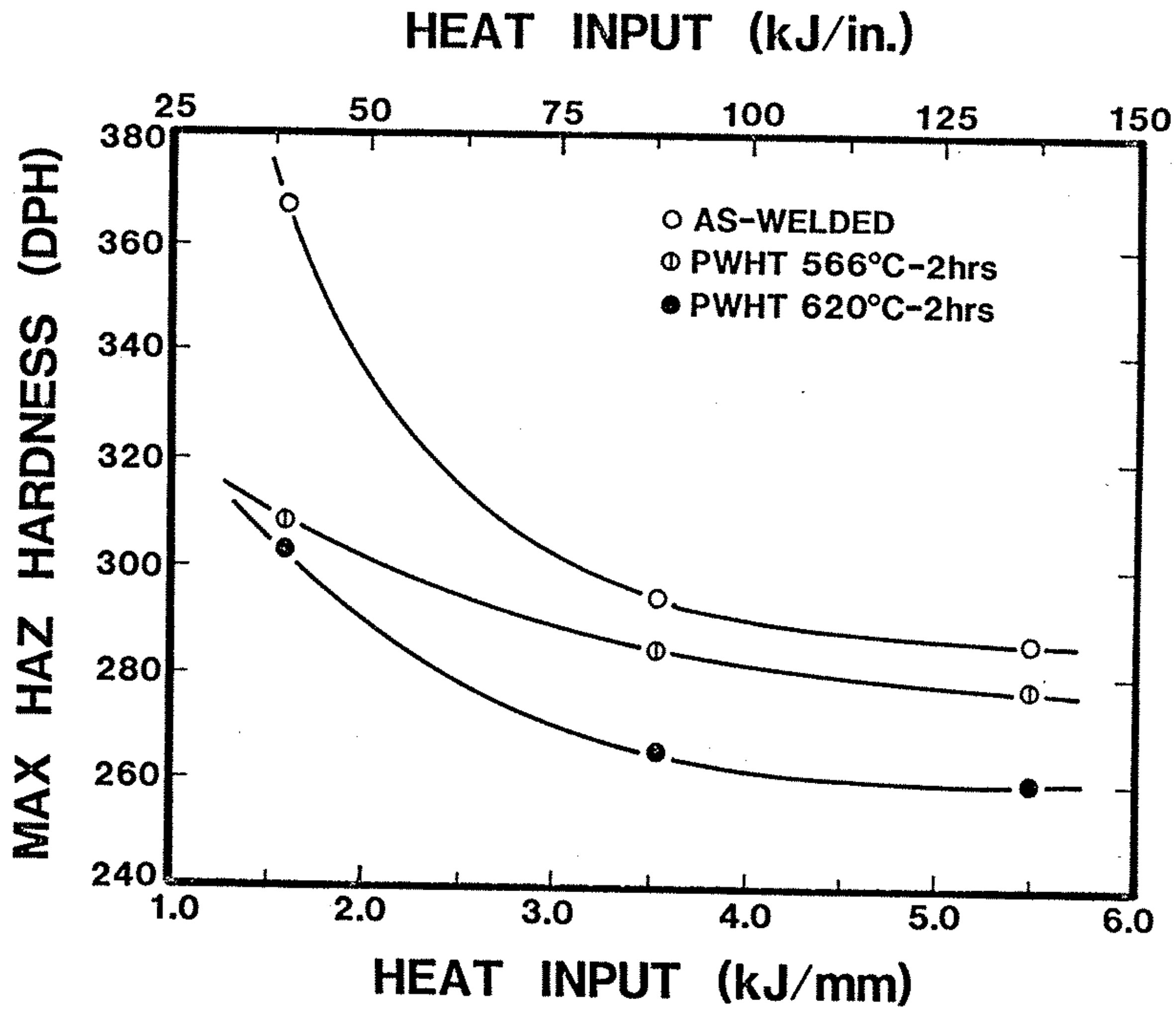


FIGURE 14. The effect of heat input and stress relief on the hardness of the heat affected zone of A588 Grade A steel (normalized).

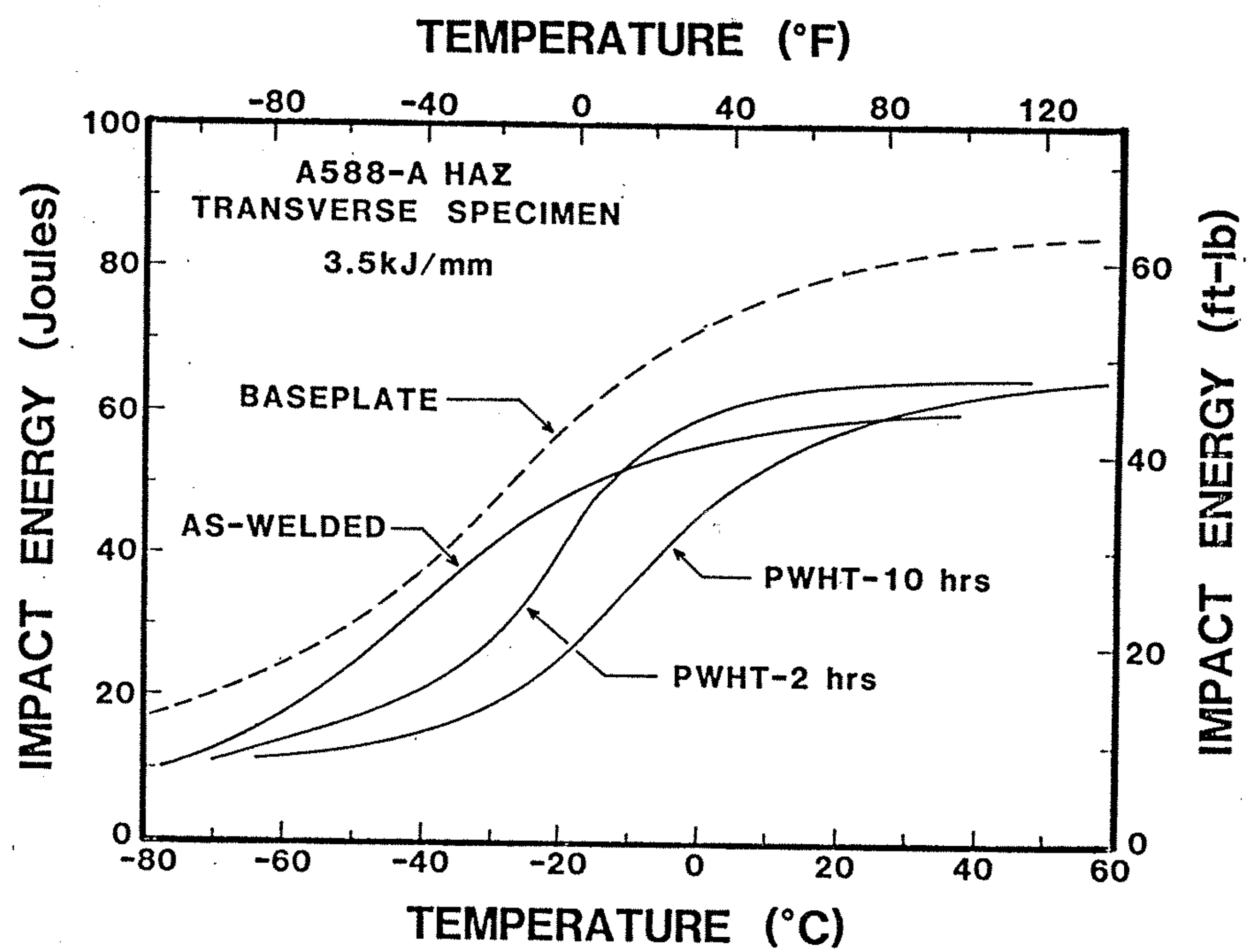


FIGURE 15. The effect of post weld heat treatment on the toughness the heat affected zone of welded A588 Grade A steel (normalized).

Designation: A 588 – 84a

American Association State
Highway and Transportation Officials Standard
AASHTO No.: M 222

Standard Specification for
HIGH-STRENGTH LOW-ALLOY STRUCTURAL STEEL WITH 50 ksi (345 MPa) MINIMUM YIELD POINT TO 4 in. (100 mm) THICK[1]

This standard is issued under the fixed designation A 588; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

This specification has been approved for use by agencies of the Department of Defense and for listing in the DoD Index of Specifications and Standards.

1. Scope

1.1 This specification covers high-strength low-alloy structural steel shapes, plates, and bars for welded, riveted, or bolted construction but intended primarily for use in welded bridges and buildings where savings in weight or added durability are important. The atmospheric corrosion resistance of this steel is approximately two times that of carbon structural steel with copper. This specification is limited to material up to 8 in. (200 mm) inclusive in thickness.

NOTE—Two times carbon structural steel with copper is equivalent to four times carbon structural steel without copper (Cu 0.02 max).

1.2 When the steel is to be welded, it is presupposed that a welding procedure suitable for the grade of steel and intended use or service will be utilized.

1.3 The values stated in inch-pound units are to be regarded as the standard.

2. Applicable Document

2.1 *ASTM Standard:*

A 6/A 6M Specification for General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, and Bars for Structural Use[2]

3. General Requirements for Delivery

3.1 Material furnished under this specification shall conform to the applicable requirements of the current edition of Specification A 6/A 6M.

4. Process

4.1 The steel shall be made by one of the following processes: open-hearth, basic-oxygen, or electric-furnace.

4.2 The steel shall be made to fine grain practice.

5. Chemical Requirements

5.1 The heat analysis shall conform to the requirements prescribed in Table 1.

5.2 The steel shall conform on product analysis to the requirements prescribed in Table 1, subject to the product analysis tolerances in Specification A 6/A 6M.

5.3 When required, the manufacturer shall supply evidence of corrosion resistance satisfactory to the purchaser.

6. Tensile Requirements

6.1 The material as represented by the test specimens shall conform to the requirements for tensile properties prescribed in Table 2.

6.2 For material under 5/16 in. (8 mm) in thickness or diameter, as represented by the test specimen, a deduction of 1.25 percentage points from the percentage of elongation in 8 in. or 200 mm specified in Table 2 shall be made for each decrease of 1/32 in. (0.8 mm) of the specified thickness or diameter below 5/16 in. (8 mm).

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[1] This specification is under the jurisdiction of ASTM Committee A-1 on Steel, Stainless Steel and Related Alloys and is the direct responsibility of Subcommittee A01.02 on Structural Steel for Bridges, Buildings, Rolling Stock, and Ships.

Current edition approved July 27 and Sept. 28, 1984. Published November 1984. Originally published as A 588 – 68. Last previous edition A 588 – 82.

[2] *Annual Book of ASTM Standards*, Vol 01.04.

TABLE 1 Chemical Requirements (Heat Analysis)

Element	Composition, %								
	Grade A	Grade B	Grade C	Grade D	Grade E	Grade F	Grade H	Grade J	Grade K
Carbon	0.19 max	0.20 max	0.15 max	0.10–0.20	0.15 max	0.10–0.20	0.20 max	0.20 max	0.17 max
Manganese	0.80–1.25	0.75–1.35	0.80–1.35	0.75–1.25	1.20 max	0.50–1.00	1.25 max	0.60–1.00	0.50–1.20
Phosphorus	0.04 max	0.04 max	0.04 max	0.04 max	0.04 max	0.04 max	0.035 max	0.04 max	0.04 max
Sulfur	0.05 max	0.05 max	0.05 max	0.05 max	0.05 max	0.05 max	0.040 max	0.05 max	0.05 max
Silicon	0.30–0.65	0.15–0.50	0.15–0.40	0.50–0.90	0.30 max	0.30 max	0.25–0.75	0.30–0.50	0.25–0.50
Nickel	0.40 max	0.50 max	0.25–0.50	...	0.75–1.25	0.40–1.10	0.30–0.60	0.50–0.70	0.40 max
Chromium	0.40–0.65	0.40–0.70	0.30–0.50	0.50–0.90	...	0.30 max	0.10–0.25	...	0.40–0.70
Molybdenum	...	...	...	...	0.08–0.25	0.10–0.20	0.15 max	...	0.10 max
Copper	0.25–0.40	0.20–0.40	0.20–0.50	0.30 max	0.50–0.80	0.30–1.00	0.20–0.35	0.30 min	0.30–0.50
Vanadium	0.02–0.10	0.01–0.10	0.01–0.10	...	0.05 max	0.01–0.10	0.02–0.10	...	...
Zirconium	...	...	...	0.05–0.15	...	...	...	...	...
Columbium	...	...	...	0.04 max	...	...	...	...	0.005–0.05[A]
Titanium	...	...	...	...	...	...	0.005–0.030	0.03–0.05	...

[A] For plates under ½ in. in thickness, the minimum columbium is waived.

TABLE 2 Tensile Requirements[A]

	Plates and Bars			Structural Shapes
	For Thicknesses 4 in. and Under (100 mm)	For Thicknesses Over 4 in. to 5 in. incl (100 to 125 mm)	For Thicknesses Over 5 in. to 8 in. incl (125 to 200 mm)	All Groups[F]
Tensile strength, min, ksi (MPa)	70 (485)	67 (460)	63 (435)	70 (485)
Yield point, min, ksi (MPa)	50 (345)	46 (315)	42 (290)	50 (345)
Elongation in 8 in. or 200 mm, min, %	18[B,C,D]	...	...	18[B]
Elongation in 2 in. or 50 mm, min, %	21[C,D]	21[C,D]	21[C,D]	21[E]

[A] For plates wider than 24 in. (610 mm), the test specimen is taken in the transverse direction. See 11.2 of Specification A 6/A 6M.
[B] See 6.2.
[C] Elongation not required to be determined for floor plate.
[D] For plates wider than 24 in. (610 mm), the elongation requirement is reduced two percentage points.
[E] For wide flange shapes over 426 lb (192 kg)/ft elongation in 2 in. (50 mm) of 18 % minimum applies.
[F] See Specification A 6/A 6M.

SUPPLEMENTARY REQUIREMENTS

Standardized supplementary requirements for use at the option of the purchaser are listed in Specification A 6/A 6M. Those which are considered suitable for use with this specification are listed by title:

S2. Product Analysis,
S3. Simulated Post-Weld Heat Treatment of Mechanical Test Coupons,
S5. Charpy V-Notch Impact Test,
S6. Drop Weight Test,
S8. Ultrasonic Examination,
S14. Bend Test,
S15. Reduction of Area, and
S18. Maximum Tensile Strength.

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